CONF-781122--4

LA-UR -78-2861

TITLE: "THE ECONOMIC PERFORMANCE OF PASSIVE SOLAR HEATING: A PRELIMINARY ANALYSIS"

AUTHOR(S): Fred Roach, Scott Noll, Shaul Ben-David

SUBMITTED TO: Presented at AIAA/ASERC Conference on Solar Energy: Technology Status, November 27-29, 1978 at Phoenix, Arizona

Proceedings will be published November 28.

los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

MASTER

THE ECONOMIC PERFORMANCE OF PASSIVE SOLAR HEATING: A PRELIMINARY ANALYSIS[1]

Fred Roach and Scott Noll
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Shaul Ben-David
The University of New Mexico
Albuquerque, New Mexico 87131

Abstract

As the interest in solar energy applications for residential space heating grows, it becomes imperative to evaluate the economic performance of alternative designs. We concentrate here on only one generic passive concept--the thermal storage wall. For the thermal storage wall we examine two types of storage medium--masonry (Trombe) and water. In addition we include a night insulation option in the thermal storage wall concept, thus giving rise to four alternative passive designs. The economic performance of these alternative designs are evaluated on a state-by-state basis. Discussion of the methodology briefly reviews the architectural design criteria, solar performance characteristics, and the incremental solar cost of each solar design. Also included is a discussion of conventional energy costs, as well as the optimal sizing/feasibility criterion employed in the economic performance analysis. Nationwide feasibility results are reviewed for each alternative design. In addition to contrasting the solar systems themselves, the effects of two incentive proposals--the National Energy Act (NEA) income tax credits and low interest loans--upon each design are examined. Finally, major conclusions are summarized for each design.

INTRODUCTION

If passive solar energy is to be considered as a viable and widely promising conservation option for new single family homes within the U.S., the economic feasibility of this option must be demonstrated. In addition, the potential energy savings from deployment of this option must be established through analysis of optimal design criterion. In this paper the emphasis is placed upon evaluating the economic performance of only one generic passive concept--the thermal storage wall. For the thermal storage wall two types of storage medium--masonry (Trombe) and water--are examined. An analysis of night insulation for both storage mediums is also included in the economic performance evaluation.

The economic performance of these four basic designs (Trombe and water walls with the option of night insulation) is evaluated on a state-by-state basis. The section on methodology briefly reviews the architectural design criteria, solar performance characteristics, and the incremental solar cost of each solar design. Also included in this section is a discussion of conventional energy costs, as well as the optimal sizing/feasibility criterion employed in the economic performance analysis. In the third section, nationwide feasibility results are reviewed for each design. In addition to contrasting the solar designs themselves, the effects of two incentive proposals--the National Energy Act (NEA) income tax credits and low interest loans--upon each design are examined. The potential for energy conservation is briefly reviewed through examination of solar fractions and fuel savings. Results are summarized in section four, with major conclusions reviewed in section five.

Methodology

There are essentially five basic steps employed in our evaluation of the economic performance of solar systems/designs. First, architectural design parameters for a standard house and solar system are established. Second, the physical performance of that system in various locales is estimated using a computer simulation code based upon a solar load ratio (SLR) correlation.[1,2] The solar performance characteristics (glazing area and storage volume) obtained from the simulation model are used to develop costs of providing alternative quantities of heat (solar fraction) for each locale. Fourth, the costs of providing heat through conventional means (natural gas, heating oil, and electricity--both resistance and heat pumps) are projected for each locale in the analysis. And finally, the potential for solar installations is examined through our performance evaluation. This evaluation includes analysis of possible energy savings through assessment of solar fractions and fuel displacements.

A standard home design[2] (approximately 1500 ft^2) is being used throughout the analysis to allow interregional comparisons. Moreover, a 'tract' home concept and common building materials were assumed. An overview of the thermal storage wall (in this case masonry or Trombe) concept, along with the 'tract' home floor plans, is presented in Fig. 1. The water wall characteristics differ slightly from those in Fig. 1, with plastic tubes (12-inch in diameter) replacing the masonry storage medium.

The modified solar ratio (SLR) correlation procedures developed by Los Alamos Scientific Laboratory[1,2] were utilized to estimate solar performance given the parameters of the above solar system designs. This procedure is capable of treating several design parameters as variables: i.e., nominal building heat loads, glazing type, number of glazings, glazing area, storage volume, and storage type. Regional variability in weather patterns are taken into account in the performance computations. The modified SLR performance correlations are used to determine the glazing area required to achieve given solar fractions for the specific solar design under analysis. The ratio of glazing area to storage volume was held constant for each of the solar designs to ease the computational burden and limit the almost infinite construction design possibilities.[3]

For the Trombe wall design and 18-inch thick masonry storage wall with double glazing is used in the solar performance analysis.[4] Mean air temperature is kept at 70°F, with a 5°F temperature swing allowed--auxillary heat required when the interior temperature drops below 65°F, and excess heat purged when the interior reaches 75°F. System performance measured by the glazing area required to provide a given solar fraction (ranging from 5 to 100 percent) was calculated for the Trombe wall design, both with and without night insulation (R-9). To calculate the performance of the water wall, a 12-inch diameter tube with the same double glazing and allowable temperature swings is used; again, both with and without night insulation.

Identical building heat loads for each of these designs were, assumed, with a standard 9 Btu/DD/Ft^2 heat load factor employed in the solar performance estimates.[5] Table I summarizes glazing area requirements to achieve representative solar fractions (portion of conventional heat replaced by solar) for all four system designs in six representative sites.

Every effort was made to construct realistic cost estimates for each solar design. In all cases we isolate the add-on solar components so that they may be priced independent of traditional home costs. The specific costs used in our analysis are displayed in Table II. Since the costs displayed represent a national average,[6] we subsequently adjust these materials and labor costs for each locale to account for regional variability.[7]

Representative solar costs, both the total ($) and average[8] ($/10^6 Btu heat provided), for each design are displayed for six representative sites in Table III. As evident, the total installed solar costs for all four passive designs increase at an increasing rate (all costs are variable). Also noted is the inability for several designs to supply more than a given fraction (.60) of total annual heat load requirements.

Although many alternative energy futures are being examined, the NEA as modified by the recent natural gas compromise in Congress is used to construct projected fuel costs.[9] A 1977 state-by-state energy data base for natural gas ($/MCF), heating oil (¢/gal), and electricity (¢/Kwh) prices has been constructed previously.[7] Future energy projections are developed: at the wellhead for natural gas and oil; at the meter for electricity; with a transportation, distribution, and marketing cost adjustment component (natural gas and heating oil only) added to arrive at delivered or metered cost. To construct equivalent delivered heating costs the above fuel prices are transformed into a $/$10^6$ Btu measure for each year. These figures are subsequently adjusted for furnace or heating equipment conversion efficiency.

Table IV displays the cost of delivered fuel for six representative sites used in the economic performance analysis. Both current and annualized prices are contrasted for 1978 and 1990. Note that nominal dollars are used. The computational procedures used in constructing both current and annualized projections are given in footnotes to the table.

An equivalent set of criteria is employed in the economic analysis of all solar energy systems/designs. Reduced to its simplest form, a series of home heating systems that include a solar component, providing anywhere from zero to 100 percent of the required heat, are evaluated to determine the economically optimal mix of solar and conventional back-up systems.[10] The net present value of a solar addition in concert with the fuel cost from a conventional furnace over the heating life is maximized. This is exactly equivalent to minimizing the cost of delivered heat to the home over a specified life time. The impact of incentives is easily integrated into this life cycle costing framework, thus allowing consistent evaluation of the economic performance of passive solar designs under various governmental policies. Because the optimal sizing/feasibility criteria has been reported previously,[6,7] further discussion is excluded from this paper.

Results

In this section, only selected results from the economic performance analysis are presented. Excluded for all four solar designs are comparisons with heating oil and electric heat pumps. Furthermore, since (a) the Trombe wall design enjoys a much wider consumer acceptance today, and (b) there is not always a great deal of difference in the pattern (number of states will vary however) of results between a Trombe and water wall design, discussion will center on the Trombe wall design (with and without the night insulation option) with only minimal reference to the water wall design.

In addition to examining the individual economic performance of each solar design, the comparative economic performance among systems is briefly reviewed. The potential for conservation is evaluated through discussions on solar fractions--the fraction of heat load formally supplied by the traditional fuels displaced by the addition of one of the four solar designs. As part of the analyses the effects of two alternative incentive options are evaluated: the NEA income tax credits,[11] here assumed applied to passive solar in the same manner as proposed for active systems, and low interest loans.[12]

If the Trombe wall without night insulation design is contrasted with natural gas, only in two states does it appear economic to install such a design in a new home: Maine in 1978 and Idaho in 1983. The water wall design without the night insulation option performs no better against natural gas: only in Maine (1983) does it appear economic to include a water wall in new home construction. The solar fraction for both designs is rather low in the two states, 10 percent. Note there are no incentives included in the economic performance evaluation of these two designs yet.

By the addition of night insulation to the storage wall concept, some additional states join the feasibility set when natural gas is the alternative fuel. This pattern is displayed in Map 1 for the Trombe wall design. Except for North Carolina, the additional states are located in New England. The solar fraction is 10 percent for all states except Maine (.30). For the water wall design, the addition of night insulation is more important. In addition to those states displayed in Map 1, a number of states in the West (North and South Dakota, Montana, Wyoming, Oregon, California, and New Mexico) along with the states of Wisconsin, Virginia, and Maryland join the feasible set. Solar fractions are either 10 or 15 percent, except for

Maine (.40). here again, incentives are not yet ·t of the economic performance analysis.

·clusion of the proposed NEA income tax ·ts[13] in the economic analysis gives rise to · larger number of states portraying economic ·bility against natural gas. As seen in Map 2 f· the Trombe wall design (with night insulation), the general location of those states achieving solar competitiveness is the New England, Midwest, Plains, and Western regions of the U.S. A portion of the Southeast region is also included in the general pattern of feasibility. By contrasting Map 2 with Map 1, it can be seen that the year of feasibility is moved forward for those states appearing in both. Generally speaking the first year of feasibility is 1978, except for those states in the Plains and Southwest regions where feasibility is delayed to the period between 1981 and 1984. Solar fractions have increased for the most part, with the range now between 10 and 25 percent in all states except Maine (.40). Thus, inclusion of the proposed income tax credits greatly enhances potential fuel savings from the Trombe wall with night insulation design due to both increased solar fractions and solar deployment in a greater number of states.

For the water wall with night insulation design inclusion of the proposed NEA income tax credits offers sufficient incentive within the economic performance analysis so as to make solar competitive against the natural gas alternative in most of the U.S. (Map 3). For the most part, those states excluded lie within or near major natural gas supply regions and have relatively low heat loads. Solar fractions are generally below 35 percent, again except for Maine (.55), but in many instances are 5 percentage points above the Trombe wall (masonry storage) design.

If low interest loans are substituted for the NEA tax credits, a larger number of states enter the feasibility set against the natural gas alternative. Map 4 portrays these results for the Trombe wall design with night insulation. In addition, for a number of states feasibility is achieved at an earlier date than when the NEA tax credit form of incentive was used in the economic performance analysis. In general, solar fractions are 5 percentage points or higher for the low interest loan option.

For the water wall design with night insulation similiar effects are noticed. Three states excluded from Map 3--Ohio, West Virginia, and Arkansas--now join the feasible set when the low interest loan option is substituted for NEA income tax credits. The year of feasibility is moved forward in a number of states, and the solar fraction is increased in over two-thirds of the states. Although not reported here, the same type of impacts occur for the Trombe and water wall designs without inclusion of the night insulation option.

When both incentive options are combined, as has been indicated in recent Congressional debate, only in Florida and Louisiana is the Trombe wall with night insulation design not economically competitive against natural gas. Only in Florida is the water wall with night insulation design shown not to be competitive. Moreover, the year of feasibility is 1978 for all states except Florida and Louisiana (Florida only in the water wall design comparison). Solar fractions are always higher than with either incentive option individually, with larger differences generally occuring in the South and West.

A somewhat different picture (from that discussed above for natural gas) emerges when electric resistance is used as the alternative fuel against which the passive solar designs must compete. Solar is measurably enhanced in its competitive position due to the higher costs ($/10^6 Btu) of electricity across the U.S. Thus, a larger number of states enter the feasible set, larger solar fractions are evident, and the actual year of feasibility is almost always 1978.

The Trombe wall without night insulation design is able to compete against the electric resistance alternative in all states except Washington without the inclusion of incentives. As portrayed in Map 5, the solar fractions range from 15 to 40 percent in all states except Arizona, California, and South Carolina--the solar fraction in these states being 5 to 10 percentage points higher. States in the Midwest and Plains regions generally have lower solar fractions than the remainder of the country. In all states, excepting Washington, the year of demonstrated solar competitiveness is 1978.

When the water wall without night insulation design is compared against the electric resistance alternative, a very similar pattern emerges (Map 6). However, there are several differences. In a number of states the solar fraction is less than for the Trombe wall. Louisiana, Kentucky, and West Virginia join the state of Washington in being excluded from demonstrated feasibility. And the year of feasibility is delayed beyond 1978 for Illinois, Michigan, Ohio, Oregon, Pennsylvania, and Tennessee. Thus, the Trombe wall design displays better economic performance than the water wall design (both without inclusion of the night insulation option). But more important for both designs is that the results reported here do show that it is cost effective now to employ passive solar in new home construction throughout the country. The potential fuel savings makes the deployment of passive solar energy a very promising conservation option for the future.

When night insulation is added to either storage wall design, there is an incremental increase in optimal solar fraction. For the Trombe wall design in only two states, Louisiana and Oregon (with Washington still excluded from economic feasibility), is the incremental increase not seen, while in the water wall design the increase occurs in all states (excepting Washington again). Map 7 contains a summary of the incremental change in all states for the Trombe wall design. As can be seen, in the majority of states the incremental change is 15 percentage points or greater. It is primarily in the Ohio River valley states (plus Arizona and California) where the incremental change is smaller (on the order of 5 to 10 percentage points). The highest change occurs in the Rocky Mountain, Northern Great Plains, and New England areas. Thus, as expected, the more severe the climate, the more important becomes the use of night insulation for the maximization of economic performance.

For the water wall design, inclusion of night insulation in the economic performance analysis gives rise to similiar improvements in solar fractions. These results are portrayed in Map 8. By comparing Map 8 with Map 6, it can be seen that many states make a two step jump; that is the states as portrayed in Map 8 are in the solar fraction range two levels above the value portrayed in Map 6. Although not readily apparent from the map portrayed, the percentage point increase is generally larger than was the case for the Trombe wall design. In addition to supporting the logical notion that night insulation is especially important in severe winter climates, the results also indicate that night insulation is more critical in the water wall design (as evidenced by higher solar fraction increments). For both designs the results essentially indicate that for a similiar dollar outlay, the consumer can purchase a more efficient solar system by adding night insulation to a storage wall concept.

[Because the maximum allowable glazing area has been constrained to account for permissible tract home characteristics (8' x 56' south-facing wall), the inclusion of incentives in the economic performance analysis will not increase optimal solar fraction in those states where the constraint is binding. Therefore, in the remaining brief discussion of results it will be seen that no visible change occurs in some northern states. However, in all cases the dollar cost paid by consumers in reaching this maximum solar fraction will be appreciably lowered.]

With the inclusion of NEA income tax credits in the economic performance analysis (electric resistance alternative), further additions are made to the optimal solar fraction in a number of states. The incremental increases are portrayed in Map 9 for the Trombe wall, and Map 10 for the water wall. As evident, tax incentives are important for they increase substantially the potential energy savings in new home construction (higher solar fractions) and lower the total system costs paid by the consumer. Although the pattern of results for the two passive solar designs are very similiar, it is generally true that for many states the incremental increase is greater for the water wall design. As shown in both maps, improvements to the conservation potential (fuel savings from higher solar fractions) from lowered solar costs is beginning to lessen due to physical construction constraints in some states.

If low interest loans are substituted for the NEA income tax credits, more states would display larger incremental changes (again against the electric resistance alternative) than those portrayed in Maps 9 and 10. In addition to a larger number of states with the now higher fractions, it is also true that more of them have hit their physical construction limits; that is additional glazing area, although economically warranted, is impossible because of the 'tract' home design limitations. As was pointed out when natural gas was the alternative fuel, the specific low interest loan incentive employed in the economic performance analysis (3 percentage points less than the mortgage rate) has greater impact on the results than the NEA income tax credits.

As expected, a combination of both incentives performs better than either individually when compared to the electric resistance alternative. The combination of incentives increases the solar fraction in all states, excepting those already limited by construction possibility--glazing area at the 'tract' home physical maximum. This higher solar fraction leads to even greater energy savings potential for much of the U.S.

Summary

The following points serve to summarize the basic findings from the preceeding analysis. As cautioned in previous work,[6,7,8] economic feasibility is a necessary, but not sufficient condition for large-scale market penetration or consumer adoption. However, the solar fractions included in the economic feasibility results do give some indication of the potential level of fuel savings given deployment of passive solar energy in new home construction.

- The addition of night insulation to thermal mass storage walls makes a significant difference, not only in the solar performance, but more importantly in the economic performance of this generic passive concept. In addition, the effectiveness of night insulation becomes greater as the severity of the climate increases.

- The potential use of passive solar designs in residential space heating applications is measurably enhanced by incentives against all fuel types. This enhancement is especially evident in the natural gas and heating oil comparisons.

- The passive designs evaluated in this paper are economically competitive against the electric resistance alternative in all but a few states. Moreover, on a life cycle cost basis these designs are feasible today.

- Employment of the low interest loan incentive option gives rise to higher solar fractions than under the NEA income tax credit option. The particular low interest loan incentive evaluated here reduces solar costs for the homeowner more than the tax credit does.

- Although the optimal solar fractions reported here for the four passive designs are generally low, the thermal mass storage wall offers one the opportunity to incorporate solar into a new home at costs much less than their active counterparts. Further, passive design offers consumers a relatively inexpensive solar option to add to his conservation alternatives.

Conclusions

Although this paper indicates the relative economic competitiveness of passive solar thermal storage walls against conventional fuel alternatives (even without federal incentives against electric resistance), the results stem from a particular set of assumptions concerning fuel escalation rates, discount rates, system life, fuel conversion efficiencies, and so forth. Additionally the designs analyzed are constrained in terms of storage to glazing area ratios, number of glazings, temperature swings (nighttime temperature set-back options were not considered), and insulation R factors. Optimal conservation strategies must consider an entire array of options, whereas this study has only considered the use of winter heat gain characteristics integrally designed into the building envelope. Additional elements of practical energy conservation include, for example, building shell heat loss prevention, better use of thermostatic and heat distribution control, proper utilization of natural lighting and ventilation potentials, and earth berming.

The above caveats are not meant to diminish the results reported here; rather, they point to the fact that passive solar architecture should be considered as a key element in energy conservation design. Sensitivity analyses will of course show that life cycle cost competitiveness varies significantly with respect to the underlying assumptions; however, if feasibility is demonstrated using a fairly conservative set of assumptions as we have done here, one can more readily accept the potential for passive solar design as an energy conservation technology.

Acknowledgements

We wish to thank the Solar Energy Group, and particularly Doug Balcomb, Bob McFarland, and Bill Wray, of the Los Alamos Scientific Laboratory for supplying us with all of the solar performance data. We also wish to thank Burns and Peters, and C. M. Inc., Bickle Division, for their assistance in developing solar designs and cost estimates.

Notes

1. This work has been supported by the U.S. Department of Energy, Assistant Secretary for Conservation and Solar Applications.

2. The Solar home design was developed by Burns and Peters, an architectural firm located in Albuquerque, New Mexico.

3. In another study as reported by Scott Noll, the constraint (a constant thermal storage to glazing area ratio) is relaxed so that the impacts of thickness variations in a Trombe wall design can be examined. For all solar designs evaluated in this paper, a ratio was selected that appears to offer a high degree of comfort.

4. For a more comprehensive examination of these design criteria, see Balcomb, Headstrom, and McFarland.[2]

5. This represents a nominal load which accounts for heat loss through all surfaces <u>except</u> the south wall.

6. Costs were developed for a given locale then adjusted to reflect national dollar averages.

7. Mean's <u>Building Construction Cost Data 1978</u>[5] was used as the principal source in adjusting the national dollar costs to specific sites.

8. Average costs are stated in annualized terms. The computational formula is given as a footnote to Table III. A more complete explanation can be found in Ben-David, et al[3], and Roach, et al.[6]

9. For a more complete explanation of the ' jection procedures, see Roach, et al.

10. A more detailed and formal description of the optimal sizing/feasibility methodology can be found in Roach, et al.[6]

11. A House-Senate Compromise version of the solar income tax credits is the specific form under review here: 30 percent of the first $1500, 20 percent on the next $8500, with a maximum of $2150 for systems $10,000 and over. The tax credits are assumed to begin in 1978 and continue at the same levels through 1984, at which point they are terminated for 1985 and following years. This particular compromise may not represent the final legialative form.

12. The specific value employed in the low interest loan incentive is 3 percent: that is the government would subsidize the difference between the going mortgage rate and the rate paid by consumers under this program at a rate 3 percentage points below the mortgage rate. In the specific analysis reported here, a mortgage rate of 9.5 percent is employed with consumer loans available for the solar components at 6.5 percent.

13. It is assumed here that the <u>add-on</u> solar costs associated with passive designs are treated in the same manner as those proposed for active systems. That is, full credit is given in our computations for the additional cost incurred for the passive designs. An alternative is to allow only a partial credit in the sense that not all the add-on cost can be used in tax credit computations. The impact of such a tax credit system has been evaluated, but the results are not included as part of this paper.

References

1. Balcomb, J. Douglas, and Hedstrom, James C., "A Simplified Method for Sizing a Solar Collector Array for Space Heating," a paper presented at "Sharing the Sun in the 1970's Solar Energy Conference, Winnepeg, Canada (August 1975).

2. Balcomb, J. D., Hedstrom, J. C., and McFarland, R. D., "Passive Solar Heating of Buildings," a paper presented at the Workshop on Solar Energy Applications, July 1977, and published in "Passive Solar Buildings: A Compilation of Data and Results," Stromberg, R. P. and Woodall, S. O., Sandia Laboratories (August 1977).

3. Ben-David, Shaul, Schulze, William D., Balcomb, J. Douglas, Katson, Roberta, Noll, Scott, Roach, Fred, and Thayer, Mark, "Near Term Prospects for Solar Energy: An Economic Analysis," <u>Natural Resources Journal</u> (April 1977).

4. Noll, Scott, "A Microeconomic Approach to Passive Solar Energy Design: Performance, Cost, Comfort, and Optimal Sizing," a paper presented at The National Conference on Practical Energy Conservation in Residential and Commercial Buildings, Baltimore, Maryland (August 1978).

5. Means Construction, <u>Building Construction Cost Data 1978</u>, 36th Annual Edition, Means (January 1978).

6. Roach, Fred, Noll, Scott, Ben-David, Shaul, and Schulze, William, "Prospects for Solar Energy: Impact of the National Energy Plan," a paper presented at the Second National Conference and Exhibition on Technology for Energy Conservation, Albuquerque, New Mexico (January 1978).

7. Roach, Fred, Noll, Scott, and Ben-David, Shaul, Bickle, Larry, and Schulze, William, "Prospects for Solar Energy: The Impact of the National Energy Plan," Los Alamos Scientific Laboratory (December 1977).

8. Roach, Fred, Noll, Scott, Ben-David, Shaul, "The Comparative Economics of Selected Passive Solar Designs in Residential Space Heating Applications," a paper presented at the Workshop for Systems Simulation and Economic Analysis for Solar Heating and Cooling, San Diego, California (June 1978).

TABLE I

REQUIRED GLAZING AREAS (FT²) FOR REPRESENTATIVE SOLAR FRACTIONS
(SIX SELECTED SITES)

Passive Solar Design		Solar Fraction				
		.15	.30	.45	.60	.75
Trombe Wall - No Night Insulation						
Albuquerque	NM	76	163	293	482	844
Madison	WI	178	444	1038	-	-
Boston	MA	144	346	711	1500	-
Seattle	WA	100	250	519	1125	-
Charleston	SC	49	109	193	316	519
Omaha	NB	144	346	675	1350	-
Trombe Wall - Night Insulation						
Albuquerque	NM	71	110	180	276	422
Madison	WI	103	241	422	675	1125
Boston	MA	89	201	338	540	900
Seattle	WA	64	132	278	466	794
Charleston	SC	33	77	128	190	293
Omaha	NB	90	199	338	519	844
Water Wall - No Night Insulation						
Albuquerque	NM	76	163	269	409	675
Madison	WI	208	563	1227	-	-
Boston	MA	159	386	711	1500	-
Seattle	WA	101	260	540	1227	-
Charleston	SC	48	106	173	260	409
Omaha	NB	157	375	711	1350	-
Water Wall - Night Insulation						
Albuquerque	NM	50	105	169	245	355
Madison	WI	103	241	409	643	1038
Boston	MA	89	199	329	500	750
Seattle	WA	67	145	260	435	711
Charleston	SC	33	73	118	171	245
Omaha	NB	89	196	321	482	750

TABLE II
DETAILED COST BREAKDOWN: THERMAL STORAGE WALLS*

Trombe Wall

Component	Material	Cost ($) Labor	Total
Masonry Concrete 18"	2.72	3.81	6.53
Paint - 2 sides	.11	.33	.44
Glazing - Glass Double 2 3/16	2.72	.82	3.54
Footing 16" Foundation	.82	.34	1.16
Header Trim or Overhang	.68	.68	1.36
Framing 4' x 8' = 24 ft_L	2.45	.41	2.86
Conventional Wall Credit			2.27
Total System			13.60
Night Insulation** Calwall Insul Curtain 4 layer R = 10.1	3.53	.82	4.35

Water Wall

Component	Material	Cost ($) Labor	Total
Water Wall Storage 12" x 8'	5.03	.54	5.57
Glazing - Glass Double 2 3/16"	2.72	.82	3.54
Footing 12" Foundation	.67	.27	.94
Header Trim or Overhang	.68	.68	1.36
Framing 4' x 8' = 24 ft_L	2.45	.41	2.86
Conventional Wall Credit			2.27
Total System			12.00

* Dollar costs are for national averages
**Used in both Trombe and water wall designs

TABLE III

TOTAL ($) AND AVERAGE* ($/10^6 B.t.u.) COST FOR REPRESENTATIVE SOLAR FRACTIONS

(SIX SELECTED SITES)

SOLAR FRACTION

Passive Solar Design	.15		.30		.45		.60		.75	
	TC	AC	TC	AC	TC	AC	TC	AC	TC	AC
Trombe Wall-No Night Insulation										
Albuquerque, NM	977	11.84	2155	13.06	3589	15.71	6398	19.35	11180	27.09
Madison, WI	2333	15.61	6114	20.48	13640	30.46	--	--	--	--
Boston, MA	2102	19.65	5066	23.68	10398	32.41	21951	51.31	--	--
Seattle, WA	1507	17.94	3767	22.43	7823	31.05	16950	50.46	--	--
Charleston, SC	529	13.70	1173	15.19	2077	17.94	3381	21.91	5592	28.98
Omaha, NB	1932	15.37	4656	18.55	9080	24.12	18160	36.17	--	--
Trombe Wall-Night Insulation										
Albuquerque, NM	898	11.39	1920	12.17	3148	13.31	4619	15.28	7379	18.72
Madison, WI	1814	12.73	4180	14.66	7314	17.20	11703	20.52	19505	27.36
Boston, MA	1727	16.91	3892	19.05	6519	21.27	10431	25.53	17385	34.04
Seattle, WA	1279	15.94	3017	18.80	5479	22.77	9258	28.85	15793	39.38
Charleston, SC	800	13.56	1090	14.79	1794	16.22	2703	18.33	4172	22.64
Omaha, NB	1598	13.33	3525	14.70	5993	16.66	9220	19.23	14982	24.99
Water Wall-No Night Insulation										
Albuquerque, NM	865	10.48	1897	11.49	3086	12.47	4770	14.45	7870	19.07
Madison, WI	2401	16.08	6502	21.78	14185	31.68	--	--	--	--
Boston, MA	2045	19.13	4967	23.22	9150	28.52	19317	45.16	--	--
Seattle, WA	1336	15.91	3442	20.49	7160	28.42	16272	48.44	--	--
Charleston, SC	451	11.67	1007	13.05	1662	14.35	2461	15.94	3877	20.09
Omaha, NB	1858	14.81	4439	17.68	8411	22.34	15981	31.93	--	--
Water Wall-Night Insulation										
Albuquerque, NM	789	10.01	1677	10.64	2683	11.34	3903	12.38	5649	14.34
Madison, WI	1649	11.57	3800	13.33	6448	15.08	10132	17.77	16368	22.96
Boston, MA	1560	15.27	3486	17.06	5782	18.87	8750	21.49	13171	25.79
Seattle, WA	1120	13.96	2625	16.36	4694	19.50	7874	24.54	12846	32.03
Charleston, SC	425	11.60	945	12.86	1530	13.84	2209	14.95	3172	17.21
Omaha, NB	1434	11.96	3158	13.17	5189	14.43	7783	16.23	12107	20.20

TC = Total AC = Average Cost

* The average cost is defined as follows:

$$AC = FCR \times \left[\frac{VC \times A(F) + FC}{LOAD \times F} \right] \quad \text{where}$$

FCR = fixed charge rate = CR + OP

VC = variable cost ($/ft^2)

A(F) = glazing (collector) areas required to obtain F

F = solar fraction

FC = fixed cost ($)

LOAD = Btu requirements for the home

AC = average cost of solar heat provided for given F

CR = capital recovery factor = $\dfrac{1}{1-\left(\frac{1}{1+i}\right)^T}$

OP = operating and maintenance expenses (expressed as a percent of solar cost)

i = r + AIR

r = real rate of interest

AIR = annual inflation rate

Values used in the derivation of these average cost figures are as follows:

r = .035

AIR = .06

i = .095

T = 30

CR = .102

OP = .005 for Trombe and Water Wall designs w/o night insulation

.01 for Trombe and Water Wall designs with night insulation

TABLE IV

COST OF DELIVERED FUEL* ($/10^6 BTU) BY FUEL TYPE--CURRENT & ANNUALIZED** PRICES IN 1978 AND 1990 DOLLARS

(Six Selected Sites)

	Natural Gas				Heating Oil				Electric Resistance				Heat Pump			
	Current		Annualized		Current		Annualized		Current		Annualized		Current		Annualized	
Location	78	90	78	90	78	90	78	90	78	90	78	90	78	90	78	90
Albuquerque, NM	2.64	10.40	8.05	70.08	6.21	13.79	12.23	25.34	12.15	27.54	24.88	56.41	6.74	13.55	12.18	24.52
Madison, WI	3.73	12.58	10.01	24.03	6.05	13.47	11.94	24.75	12.20	27.66	24.98	56.63	8.81	17.72	15.93	32.06
Boston, MA	5.06	15.25	12.43	28.88	6.44	14.25	12.64	26.17	15.97	36.20	32.69	74.12	9.67	19.46	17.50	35.21
Seattle, WA	4.25	13.63	10.96	23.93	6.36	14.09	12.50	25.88	5.24	11.88	10.73	24.32	2.92	5.87	5.29	10.63
Charleston, SC	2.96	11.04	8.63	21.24	6.24	13.85	12.28	25.44	13.72	31.11	28.10	63.71	6.60	13.28	11.94	24.02
Omaha, NB	2.59	10.29	7.96	19.89	6.10	13.57	12.03	24.94	12.08	27.38	24.71	56.07	7.87	15.84	14.24	28.66

*Corrected for combustion effeciency as follows:

Gas = .75
Oil = .60
Electric Resistance = 1.00
Heat Pump = variable COP by location

**The Annualized cost in year t' is defined as $A_{t'} = CR \times \sum_{t=1}^{T} \left(\frac{1}{1+i}\right)^t C_{(t+t')}$

where:

$C_{t'}$ = current delivered cost ($/10^{6}Btu) in year t'

i = nominal discount rate = r + AIR

T = system life in years

CR = capital recovery factor = $\dfrac{1}{1-\left(\frac{1}{1+i}\right)^T}$

t' = 1,13 (1979-1990)

$A_{t'}$ = annualized delivered cost ($/10^6 Btu) in year t'

r = real discount rate

AIR = annual inflation rate

Values used in the derivation of these figures are as follows:

r = .035
AIR = .06
i = .095

T = 30
CR = .102 (This assumes mortgage & nominal discount rates are identical.)

TABLE V

TOTAL ($) AND AVERAGE* ($/10^6 Btu) COST FOR REPRESENTATIVE SOLAR FRACTIONS
(SIX SELECTED SITES)

SOLAR FRACTION

Solar System Design	.15** TC	.15** AC	.30 TC	.30 AC	.45 TC	.45 AC	.60 TC	.60 AC	.75 TC	.75 AC
Trombe Wall-No Night Insulation										
Albuquerque, NM	977	11.84	2155	13.06	3889	15.71	6388	19.35	11180	27.09
Madison, WI	2333	15.63	6114	20.48	13640	30.46	--	---	---	---
Boston, MA	2102	19.65	5066	[illegible]	10398	32.41	21951	51.31	---	---
Seattle, WA	1507	17.94	3767	[illegible]	7823	31.05	16950	56.46	---	---
Charleston, SC	529	13.70	1173	15..9	2077	17.96	3381	21.91	5592	28.98
Omaha, NB	1932	13.39	4656	[illegible]	9080	24.12	18160	36.17	---	---
Trombe Wall-Night Insulation										
Albuquerque, NM	898	11.39	1920	12.17	3148	13.31	4819	15.28	7379	18.72
Madison, WI	1814	12.73	4180	14.66	7314	17.20	11703	20.52	19505	27.36
Boston, MA	1727	16.91	3892	19.05	6519	21.37	10431	25.53	17385	34.06
Seattle, WA	1279	15.94	3017	18.80	5479	22.77	9258	28.85	15793	39.38
Charleston, SC	800	13.56	1090	14.79	1794	16.22	2703	18.33	4172	22.64
Omaha, NB	1598	13.33	3525	14.70	5993	16.66	9220	19.23	14982	24.99
Air Collector/Rock Storage										
Albuquerque, NM	3716	26.59	4059	24.21	5276	20.97	6893	20.55	6297	22.18
Madison, WI	4489	22.20	5977	19.17	8824	19.40	12760	21.04	18541	24.46
Boston, MA	4274	29.50	5548	25.53	7952	24.40	11186	25.74	15951	29.36
Seattle, WA	3830	33.67	4918	28.82	7236	28.27	10728	31.44	16466	38.60
Charleston, SC	3158	60.41	3673	46.84	4632	39.38	5062	37.38	7580	38.67
Omaha, NB	4217	24.80	5433	21.31	7737	20.23	10828	21.23	15436	24.21

TC = Total AC = Average Cost

*The average cost is defined as follows:

$$AC = FCR \times \left[\frac{VC \times A(F) + FC}{LOAD \times F}\right] \quad \text{where}$$

- FCR = fixed charge rate = CR + OP
- VC = variable cost ($\$/ft^2$)
- A(F) = glazing (collector) areas required to obtain F
- F = solar fraction
- FC - fixed cost ($)
- LOAD = Btu requirements for the home
- AC = average cost of solar heat provided for given F
- CR = capital recovery factor = $\dfrac{1}{1-\left(\frac{1}{1+i}\right)^T}$

- OP = operating and maintenance expense (expressed as a percent of solar cost)
- i = r + AIR
- r = real rate of interest
- AIR = annual inflation rate

Values used in the derivation of these average cost figures are as follows:

- r = .035
- AIR = .06
- i = .095

- T = 30
- CR = .102
- OP = .005 for Trombe Wall design w/o night insulation
  - .01 for Trombe Wall design with night insulation
  - .015 for Air Collector/Rock Storage system

**For Air Collector/Rock Storage active system the first representative fraction is . instead of .15.

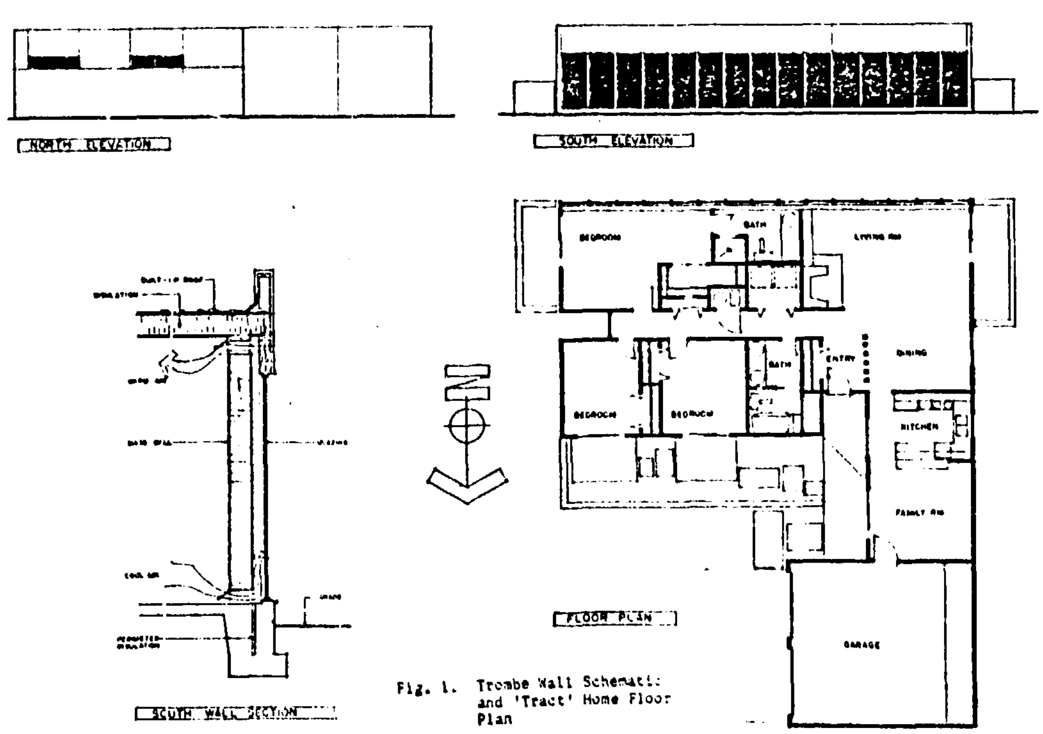
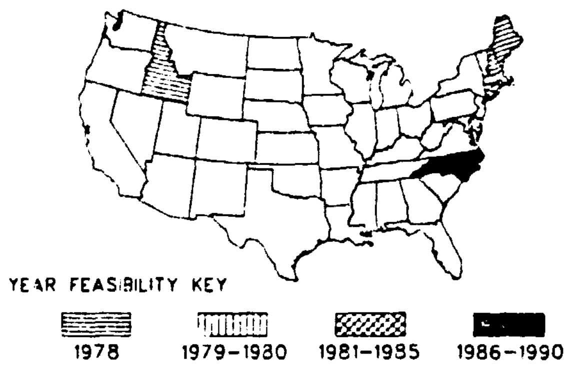


Fig. 1. Trombe Wall Schematic and 'Tract' Home Floor Plan

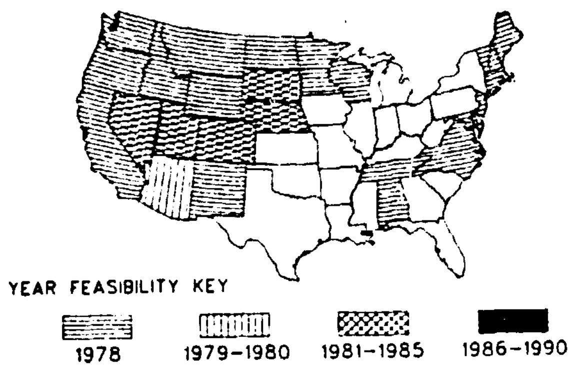
Map 1

SOLAR FEASIBILITY FOR TROMBE WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – NATURAL GAS
NO INCENTIVES
(30-YEAR LIFE CYCLE COST BASIS)



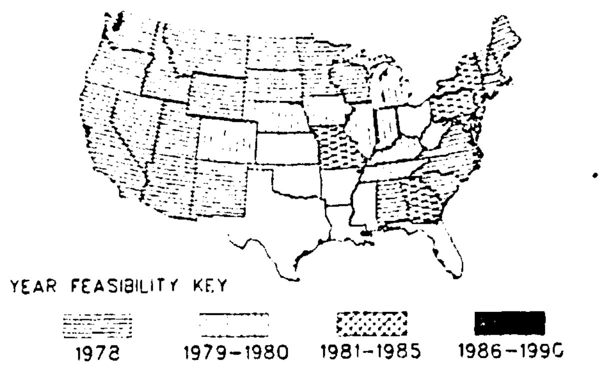
Map 2

SOLAR FEASIBILITY FOR TROMBE WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – NATURAL GAS
NEP TAX CREDIT INCENTIVE
(30-YEAR LIFE CYCLE COST BASIS)



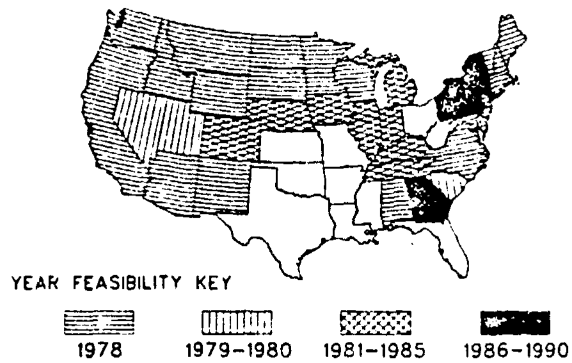
Map 3

SOLAR FEASIBILITY FOR WATER WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – NATURAL GAS
NEA TAX CREDIT INCENTIVE
(30-YEAR LIFE CYCLE COST BASIS)



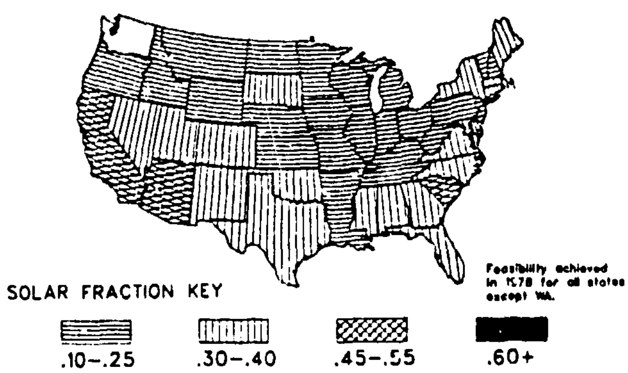
Map 4

SOLAR FEASIBILITY FOR TROMBE WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – NATURAL GAS
LOW INTEREST LOAN INCENTIVE
(30-YEAR LIFE CYCLE COST BASIS)



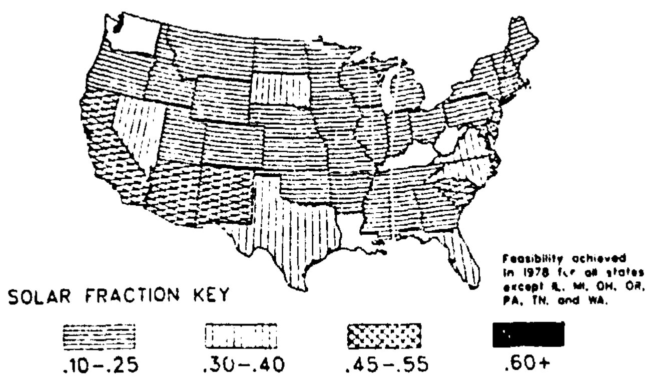
Map 5

SOLAR FEASIBILITY FOR TROMBE WALL W/O NIGHT INSULATION
ALTERNATIVE FUEL – ELECTRICITY (RESISTANCE)
NO INCENTIVES
(30-YEAR LIFE CYCLE COST BASIS)



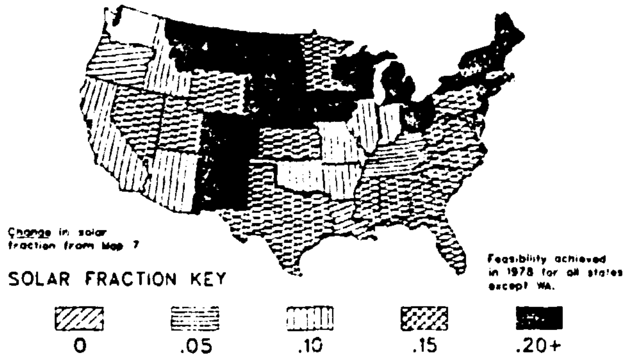
Map 6

SOLAR FEASIBILITY FOR WATER WALL W/O NIGHT INSULATION
ALTERNATIVE FUEL – ELECTRICITY (RESISTANCE)
NO INCENTIVES
(30-YEAR LIFE CYCLE COST BASIS)



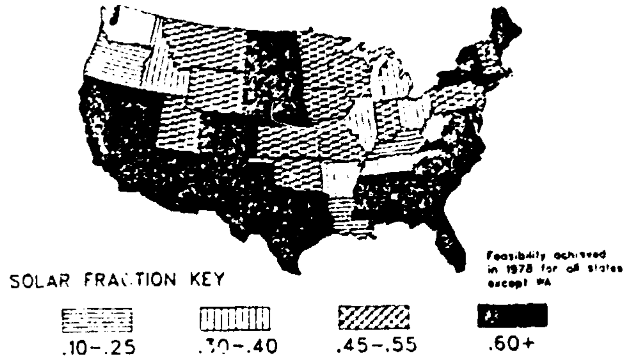
Map 7

SOLAR FEASIBILITY FOR TROMBE WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – ELECTRICITY (RESISTANCE)
NO INCENTIVES
(30–YEAR LIFE CYCLE COST BASIS)

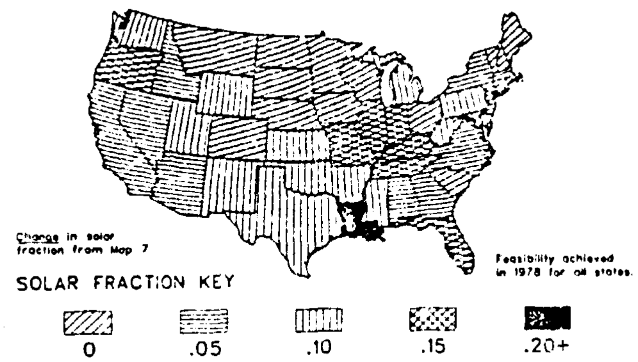


Map 8

SOLAR FEASIBILITY FOR WATER WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – ELECTRICITY (RESISTANCE)
NO INCENTIVES
(30–YEAR LIFE CYCLE COST BASIS)



SOLAR FEASIBILITY FOR TROMBE WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – ELECTRICITY (RESISTANCE)
NEP TAX CREDIT INCENTIVE
(30–YEAR LIFE CYCLE COST BASIS)



SOLAR FEASIBILITY FOR WATER WALL WITH NIGHT INSULATION
ALTERNATIVE FUEL – ELECTRICITY (RESISTANCE)
NEA TAX CREDIT INCENTIVE
(30–YEAR LIFE CYCLE COST BASIS)